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AN EXPERIMENTAL PROGRAM TO DETERMINE THE ENVIRONMENTAL IMPACT OF EXPLOSIVE REMOVAL OF OIL WELLHEADS

by

Thomas B. Heathcote

Explosion Dynamics Branch

TABLES

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ABSTRACT

Scaled models of offshore oilwells were severed explosively using three different explosive materials. Shock wave and bubble data gathered from wellheads buried in the river bottom were compared with those obtained from free water wellhead tests and also with results from free water firings of each of the three explosives contained only in PVC canisters. When buried, peak pressure, impulse and energy values were attenuated significantly from free water values at near-identical ranges.

Cube-root scaling proved valid for charge weight selection and the successful severing of the wellheads appeared to be independent of explosive type and boostering methods. The results indicate that multi-string casings with outside diameters up to 30 inches can be severed with any one of several explosive compositions weighing about 50 lbs.

Data gathered from these tests will be combined with existing data from free water fish kill studies and a plausible method will be established for predicting kill probability associated with explosive severing.

I. INTRODUCTION

The continuing increase in the world wide demand for petroleum products has resulted in proposals to conduct offshore drilling operations in hitherto protected areas. More often than not the most potentially productive locales are also the habitat of large concentrations of fish and other marine life; one such area is the Gulf of Alaska.

One integral part of offshore drilling activities is the removal of well heads that, for any of a number of reasons, have been abandoned. Federal regulations require that the vertical members of the drilling arrays - conductors, casings, tubing, cement filled annuli - be severed at some point well below the ocean floor. The subfloor severing that facilitates salvage of equipment and thus minimizes the possibilities of future navigational or fishing problems due to protruding well members, is usually accomplished by use of hydraulic or explosive type cutters.

Many operators prefer the explosive type cutting method because of the economics involved. Experience has shown that for most conditions, severing and retrieving of casing, up to 30 inches in diameter, can be effected explosively in one operation. Since each operation represents a dramatic increase in operational costs, the quickness and the dependability of the explosion method of abandonment is especially attractive.

While preferred and utilized extensively in the removal of bulkheads, the explosive concept presents problems in some areas. Most of the problems are associated with the environmental impact with special emphasis on mortality rate of marine life in the region affected by the detonation of the explosive charge. The range at which fish are killed is dependent on several factors -- the intensity of the explosion shock wave as determined by the type and configuration of explosion used, modification of the shock wave due to bottom material and water conditions (temperatures, salinity, etc.) and the susceptibility of specific species of fish to the various explosion parameters. Since only fragmentary data pertinent to fish kill are available from past explosive severings, and with accelerated offshore explorations imminent, the need for establishing the environmental effects of explosive wellhead removal becomes apparent. Consequently, NSWC has been funded by the U. S. Geological Survey, to determine the environmental effects attributable to explosive severings so that standards for the use of explosives can be established. Although the area of immediate interest is the Gulf of Alaska, it is expected that the aforementioned standards will, in general, be applicable to most offshore drilling sites.

The Naval Surface Weapons Center proposed that a program be conducted in two phases. Plans were effected to conduct Phase I, a series of model wellhead severings aimed at establishing preliminary environmental effects, at the NSWC Dahlgren site. Phase II would be a full scale test (or tests) using an actual wellhead in the Gulf of Alaska or another site more convenient.

Phase I has been completed and the results obtained are reported here.

PRELIMINARY STUDIES

A total of 52 organizations, determined from a literature search to be involved in various facets of offshore oilwell operations, were contacted by telephone. The organizations contacted are a representative sample of the oil industry.

Information gleaned from these conversations was evaluated with respect to its applicability to the proposed program and eight sources were selected for further discussions. Visits were made to the facilities of the eight organizations, all of which were located in the Gulf Coast area by NSWC personnel; information pertinent to the proposed program was exchanged.

The most significant conclusions to be drawn from the discussions are the following:

1. Most drilling operators prefer explosive severing if government controls do not become so stringent that the methods become cost prohibitive.

2. Explosive severing is the quickest and most reliable method for cutting multi-string casings of up to 30-in. diameter instantaneously.

3. Nitromethane is the basic explosive component used for most wellhead removals. Comp C-4, liquified PETN, and in very infrequent cases, packed dynamite are also used for wellhead cutting.

4. Cylindrical cannisters positioned inside the production casing 15 to 20 ft below the mudline are the most commonly used configurations for wellhead abandonment.

5. Depending on the number, diameter, and the wall thickness of the casings, and to available funds, explosives, ranging in weight from 26 to 150 lb, have been used in cutting operations.

6. Double end initiation, exploding bridge wire (EBW), and to a lesser extent, single point initiation are most apt to be used for charge detonation. Knotted Detacord is often used as a booster - if the explosive characteristics of the main charge dictates the need for boostering.

7. That fish tend to congregate in the proximity of drilling operations has been confirmed by most drilling superintendents. Essentially no data has been recorded that relate to numerical fish mortality positively attributable to explosive type severing.

The information from the above discussions was evaluated, and where relevant, applied to the planning of the model tests for Phase I of the program.

EXPERIMENTAL DETAILS

Where practical, the components comprising the experimental array - casings, charge burial depth, etc., were scaled to half size.

Cube root scaling was applied to selection of charge size for the model tests. Structural response tests where models are used have been valid when the length scale ratio is less than or equal to ~4. Since the wellhead casings were reduced to 1/2 then the value of 4 reduces to 2 and

$$\left(\frac{W_p}{W_m}\right)^{1/3} \leq 2$$

$$W_m \geq \frac{W_p}{2^3} \geq \frac{W_p}{8}$$

Where

W_p = prototype charge weight, pounds

W_m = model charge weight, pounds

Since the aforementioned discussions with personnel engaged in wellhead removal revealed weights of severing charges ranging from ~25 pounds to over a hundred pounds (dependent on application) an arbitrary prototype weight of ~50 pounds was selected. If W_p = 56 lb, then W_m = 7.0 lb.

The explosives chosen for the severing charges were a sensitized nitromethane (NM), Comp C-4, and TNT. The latter two types were cast into polyvinylchloride (PVC) cylinders at the casting facility at NSWC, White Oak Laboratory. The NM/sensitizer was mixed and loaded aboard a test platform just prior to each test. Since preliminary estimates, based on limited underwater data, indicated that the overall explosive output of Comp C-4 and TNT was less than that of NM/sensitizer mixtures, they were cast to a slightly heavier weight than that of the NM mixture. TNT, while seldom used in severing operations, is frequently used as the reference explosive for comparing the underwater performance of other explosive compositions; it was included primarily for the same purpose in these tests. Where needed, small pentolite cones were used to boost the main charges. One booster was used on the TNT charges and two were used on each of the NM configurations; none was required for the Comp C-4. Engineers Special Electric detonators were used to initiate all charges. Information relevant to the charges fired is shown in Table 1; charge configurations are displayed on Figure 1.

Steel pipes, with outside diameters of 15, 8 and 4.5 inches, were used to simulate the wellhead casings. The annuli between the casings were filled with Class "G" cement, a type commonly used in underwater structures; a sketch of the wellhead components appears as Fig. 2. The two larger diameter pipes were 15-feet in length; the inner casings were extended to a point above the water-air interface to facilitate lowering of the severing charges to the desired depth prior to each test.

A total of nine tests were conducted. One charge of each of the three compositions, using only the explosive canister, was fired in free water. A second series, with charges inside the wellhead casings, was also done in free water. For the final series, the wellheads were implanted in a mud river bottom at a site, determined from surveys conducted by the NOAA research ship Aquarius (Chesapeake Bay Biological Laboratory, Solomons, MD), best suitable for our requirements. The geographical locations for the buried wellhead tests, both on the Potomac River near Dahlgren, Va., are shown on Figure 3. The explosives were lowered through the inner casing and detonated 7.5 feet below the river bottom.

Shock wave recording gages were positioned at points in the experimental array that were expected to provide the most appropriate data for mapping the pressure field adjacent to the underwater blast from the three test configurations. Data from the two free water series were used to compare the output of the charges alone as opposed to that from the cased charges. Data obtained from the buried charges were compared with those from controlled tests designed to assess the effects of underwater explosions on marine life. The gage-charge orientation for the three series are shown in Figures 4, 5 and 6. As can be noted on Figure 6, most of the gages were concentrated at or near the mud-water interface or along the 4.5-in. diameter casing that extends to the water surface. It is at those geometries that many types of marine life are thought to be most vulnerable to the effects of sub-sea explosions. Although not included as a means of obtaining data germane to the primary objective of the program, the gages at the surface served a meaningful purpose -- acquisition of data from which a shock factor may be determined for a platform or vessel positioned almost directly over the underbottom blast. Such information should be of special interest to drilling operators who, because of the economics involved, would prefer not to move the drilling platforms when explosive wellhead removal is involved.

INSTRUMENTATION

Two AMPEX 2200 tape recorders located aboard an electronic instrumentation trailer on the EU-3 experimental barge, were used to record the shock wave signals emanating from the explosions. The recording network provided the capability for 22 shock wave channels to record the shock wave signals impinged on the tourmaline piezoelectric gages dispersed in the patterns shown on Figs. 4, 5 and 6; other channels were used for fiducial, time code, arrival times, etc. Ancillary equipment required for determining shock wave propagation velocity, water salinity and conductivity, etc., was also utilized on all experiments.

DATA REDUCTION

The shock wave signals recorded by the P.E. gages and transmitted to the recorders in the form of analog frequency-modulated magnetic tape data were converted to digital information on tape by using the Nicholet digitizing system.

The digital data for each record, together with calibration constants, were processed by using the data reduction program TIMCON to obtain shock wave parameters for each pressure-time record. The parameters evaluated included Theta, the time constant of the initial exponentially decaying portion of the shock wave after the shock front, P_{max}, the extrapolated peak pressure, E, the energy flux density, and I, the impulse. Ordinarily the information derived from TIMCON is used as input data for the computer program PARAM to obtain simulitude equations for each of the parameters for each shot. The fits are made by the method of least square to an exponential function. The parametric equations are of the form:

$F = K\, W^{1/3}\, (W^{1/3}/R)^{\alpha}$, except for peak pressure which has the form

$P_{max} = K\, (W^{1/3}/R)^{\alpha}$.

R is the distance from the central part of the charge to the gage, K is a constant for the particular parameter, and α is an exponent for the particular parameter.

However, a charge shape effect introduced by the length: diameter (ranging from 2.38 to 2.90) and the dispersion of the gages away from a common charge-gage plane precluded the establishment of valid similitude equations for the explosives. Data input for developing free water equations are usually generated from explosive yield from charges with a nominal 1.0 length: diameter ratio. In the absence of similitude equations as the bases for comparison of the underwater performance of the three explosives fired under identical test conditions or the change in output of each when test conditions were changed, an alternate method of evaluation was used. Values derived from the two free water series were compared individually at each gage position and the degradation of the shock output due to the heavy confinement proffered by the wellhead was noted. Additionally, the underwater performance of the buried charges was compared with that of the PVC cased charges fired in free water. Data were collected from, where possible, stations at identical standoffs; interpolations were used where slightly dissimilar distances existed.

Since finalization of the severing process is felt to be attributable (in large part) to the bubble energy exerted on the wellhead components, bubble periods and subsequently bubble energies were determined on all tests. As is generally done, the evaluations were made on a relative basis using the following method:

$$RBE = \left(\frac{K_{experimental}}{K_{reference}}\right)^3$$

where K* = bubble coefficient (sec-ft$^{5/6}$/W$^{1/3}$)

*In this work, reference K is the coefficient for free water PVC cased charges of each composition; experimental K's represent either free water wellheads or buried wellheads.

ARRAY DEPLOYMENT AND RETRIEVAL

Once the appropriate test site in the areas depicted on Fig. 3 had been selected and the experimental platform moored, the surrounding area was monitored for fish concentration. The monitoring was accomplished by use of two fish detectors. One was housed aboard a barge and the other, a portable unit, located on a small support vessel; coverage by the latter extended to about a 200 yard radius and 360° around the anticipated blast site. Charts of the monitoring operations were filed for future reference if the need arises.

PVC cased charges were fired at mid-depth in about 70-ft of water. Free water wellhead tests were oriented in such a manner that the charge-to-gage standoffs were identical with those of the bare charge tests and yet assured protrusion of the inner casing above the water surface for positioning the explosive. After mounting and arming the PVC cased charges, the experimental array consisting of the charge, gages, weights, floats, etc., was lowered from the deck of the recording barge into the water and floated to the designated firing site using the prevailing tide. A sea anchor was used to maintain proper array alignment. For the free water wellhead tests, the wellhead was placed in the water, secured to a work platform from which the charge was lowered to the desired depth in the wellhead, the remainder of the array placed in the water, and the complete unit floated to the firing site. A sketch of the free water arrangement for the wellhead tests appears as Fig. 7. For the buried charge tests, a crane located aboard a support barge was used to set the wellhead in the river bottom*. Prior to detonating the severing charge the instrumentation barge and the support barges were backed away from the surface zero of the wellhead to a distance well within the acceptable shock factor range established for the recording barge.

Following the explosions, the severed sections were recovered and were brought aboard for observation and evaluation.

RESULTS

Visual observations. For the six tests in which the charges were fired inside the casings, complete severing of the wellhead at the point of detonation occurred. The severings were apparently independent of charge composition, boostering methods and/or the number of initiation points. No differences attributable to the increased confinement presented by the mud on the buried charge tests were observed on the retrieved wellhead components from the six cased charge tests.

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*When in test position, the center point of the severing charge contained in the buried wellhead was 7.5 feet below the river bottom. This depth represented a severing depth of 15-ft for a prototype cutting.

Shock wave Data. The underwater performance of the three explosive mixtures when tested in the three dissimilar modes of confinement was evaluated. Measured values of peak pressure, impulse and energy flux at individual gage stations for the three firing conditions are shown in Tables 2, 3 and 4. Since a valid time constant value could not be determined for gages at many stations, the impulse and the energy parameters were integrated arbitrarily to 1.0 millisecond. (Generally the integrations are done to some multiple of the time constant and subsequent relative comparisons made of values at that time; i.e., 5θ. 7θ, 10θ, etc.) In the discussion to follow, the blast yield of the PVC cased free water explosions will serve as the standard for comparison. Values from both free water and buried wellhead tests will be compared with those of the PVC cased charges in the manner described previously.

Free Water Wellhead Relative to PVC Case

The observations noted below are the result of an evaluation of the individual relative values included in Table 5.

Peak Pressure. Decrease ranging from 30 to 55 percent occurred for the cased charges. No trend due to gage standoffs was apparent. No significant differences in pressure levels that ranged from about 1800 to 12,000 psi were discernible for the three compositions.

Impulse. Reductions of from 50 to 65 percent were disclosed for the cased charges. The calculated values at levels from about 1.70 to 0.450 psi-sec showed the decrease in output for Comp C-4 to be slightly less than that from the TNT or NM.

Energy. The decrease in shock wave energy for the cased charges was shown to be from 50 to 85 percent; standoff distance was no factor. As was the case for the impulse parameter, the attenuation of energy for Comp C-4 was slightly less pronounced.

Buried Wellhead Relative to Free Water PVC. As noted earlier, dissimilar experimental requisites for the free water and the buried charge tests required some degree of interpolation in determining relative values at some gage stations. It is felt however, that any anomalies introduced by interpolation are inconsequential in the overall relative comparison. Individual relative results appearing in Table 6 served as a basis for the notations to follow.

Peak Pressure. Pressures of the buried charge of Comp C-4 and NM relative to those of free water charges of the same compositions were down from between 50 to 80 percent; TNT was down 75 to 90 percent.

Impulse. Comp C-4 and NM were decreased from about 60 to 90 percent when the charges were buried; TNT between 80 and 90.

Energy. For the Comp C-4 and the NM charges the energy yield was attenuated by up to 90 to 95% when buried; TNT was down by nearly 95 percent at all stations.

Impulse and energy values for the free water wellhead charges and the buried wellhead charges relative to free water PVC cased charges are displayed graphically on Figures 8 and 9, respectively.

BUBBLE RESULTS

The explosion bubble energies of the TNT and the NM for the free water tests with charges in wellhead casings and the buried charges were compared to those determined for the free water PVC cased charges. The bubble periods and resultant relative energies are shown below.

	PERIOD (MS)				$RBE_{(FW-PVC)}$		
Explosive	FW PVC Case	FW Casings	Buried	Explosive	FW PVC Case	FW Casings	Buried
Comp C-4	304	279	237	Comp C-4	1.00	0.75	0.89
TNT	304	266	226	TNT	1.00	0.67	0.64
NM	300	268	227	NM	1.00	0.66	0.73

It is interesting to note that the RBE's determine for the buried charges are equal to or greater than those obtained for the free water test with the charges and the wellhead casings - an indication that energy losses do possibly to jetting to the atmosphere through the inner casing or lessened by the confinement presented by the mud surrounding the buried charges.

SUMMARY

Six attempts, three in free water and three in mud, were made to sever the model wellheads; all were successful.

The cutting capability was independent of explosive type and boostering method.

When buried, peak pressure, impulse and energy values were decreased up to 90, 89 and 99 percent respectively, from free water values at near-identical ranges.

Cube-root scaling proved valid for charge weight selection. The results indicate that multi-string casings with outside diameters up to 30-inches can, under most circumstances, be severed with any one of several conventional explosive compositions weighing from between 25 to 43 pounds.

The information presented in the preceding sections is based primarily on the results of somewhat limited empirical studies. These data have been combined with those obtained in previous studies relating to the environmental effects of underwater (or near an air-water interface) explosions - references 1, 2, 3 and prospective standards applicable to most explosive type wellhead abandonment established; details of this assessment and subsequent standardization are described in a separate report.

REFERENCES

1. Young, G. A. and Willey, R. F., "Techniques for Monitoring the Environmental Effects of Routine Underwater Explosion Tests Report (U)," NSWC/NOL TR 76-161.

2. Goertner, John F., "Dynamical Model for Explosion Injury to Fish Report," NSWC/NOL TR 76-155.

3. Goertner, John F., "Fish Killing Potential of a Cylindrical Charge Exploded Above the Water Surface Report," NSWC/NOL TR 77-90.

TABLE 1

CHARGE DETAILS

Shot No.	HE Weight (lb)	Booster Weight (lb)	HE Density (gm/cc)
	Comp C-4		
1572	7.00	0.00	1.64
1575	7.02	0.00	1.64
1578	7.00	0.00	1.64
	TNT		
1573	7.00	0.52	1.61
1576	6.80	0.51	1.61
1579	7.00	0.50	1.61
	NM/Sensitizer		
1574	6.01	0.97*	1.128
1577	6.03	0.98*	1.128
1580	6.00	0.96*	1.128

*Total weight of upper and lower boosters

TABLE 2 MEASURED SHOCK WAVE VALUES

FREE WATER-CHARGES IN PVC CASES ONLY

GAGE POSITION	RADIAL STAND-OFF (FT)	VERTICAL STAND-OFF** (FT)	PM (PSI)			I(PSI-SEC)*			E(IN-LB/SQ-IN)*		
			COMP C-4	TNT	NM	COMP C-4	TNT	NM	COMP C-4	TNT	NM
1	5.0	-2.5	7488	7711	7108	1.401	1.417	1.351	752	775	692
2	4.7	-8.5	8699	8804	7998	1.157	1.578	1.515	918	950	818
3	4.0	0	10382	10464	10071	1.677	1.758	1.700	1241	1277	1189
4	4.0	0	10227	10224	10101	1.743	1.739	1.744	1244	1241	1222
5	6.4	5.0	5644	5111	4477	1.123	1.190	1.192	543	522	491
6	6.7	5.0	4861	4278	3775	1.033	1.070	1.094	448	399	400
7	10.8	10.0	3002	2546	2187	0.575	0.697	0.654	84	165	139
8	14.1	17.5	1825	1773	1660	-	0.492	0.504	-	80	81
9	15.1	14.6	1772	1599	1486	0.451	0.441		76	68	68
10	9.6	-2.3	3866	3794	3647	0.691	0.686	0.666	177	170	161
11	9.2	-2.3	3833	3679	3623	0.698	0.691	0.680	180	173	166
12	9.0	0	3990	3851	3875	0.754	0.747	0.746	211	202	201
13	9.0	0	4284	4166	4284	0.770	0.759	0.887	222	212	288
14	10.1	5.0	3807	3498	3611	0.700	0.682	0.691	180	167	170
15	10.6	5.0	3333	3395	3062	0.682	0.665	0.644	170	158	148
16	16.9	14.3	1851	1747	1555	0.419	0.404	0.409	61	55	54
17	14.4	-2.4	2674	2587	2500	0.484	0.472	0.465	82	77	75
18	14.3	-2.4	2316	2301	2281	0.491	0.494	0.492	84	82	81
19	14.1	0	2441	2402	2429	0.497	0.500	0.493	86	84	82
20	14.9	5.1	2463	2284	2230	0.474	0.466	0.470	79	75	75
21	17.2	10.0	1805	1755	1673	0.419	0.406	0.410	59	55	56
22	13.5	10.0	2329	2215	1970	0.532	0.519	0.526	97	90	90

* Integrated to 1.0-Ms

**Indicates gages located below charge center

TABLE 3 MEASURED SHOCK WAVE VALUES

FREE WATER-CHARGES IN WELLHEAD

GAGE POSITION	RADIAL STAND-OFF (FT)	VERTICAL STAND-OFF** (FT)	PM (PSI)			I (PSI-SEC)*			E (IN-LB/SQ-IN)*		
			COMP C-4	TNT	NM	COMP C-4	TNT	NM	COMP C-4	TNT	NM
1	5.0	-2.5	4349	4952	-	0.649	0.650	-	203	236	-
2	4.7	-2.5	4395	4747	3232	0.669	0.604	0.519	201	205	152
3	4.0	0	-	6056	6106	-	0.731	0.710	-	331	315
4	4.0	0	5953	5289	6472	0.848	0.781	0.810	375	313	376
5	6.4	5.0	3086	1845	2007	0.629	0.474	0.393	156	85	78
6	6.7	5.0	-	1509	2059	-	0.341	0.436	-	55	82
7	10.8	10.0	1112	812	908	0.273	0.241	0.255	35	22	24
8	14.1	17.4	895	683	643	0.141	0.186	0.203	11	13	14
9	15.1	14.6	813	573	575	0.209	0.167	0.171	17	11	11
10	9.6	-2.3	2392	2402	2075	0.345	0.307	0.303	61	55	52
11	9.2	-2.3	2517	2233	2383	0.362	0.279	0.298	63	46	52
12	9.0	0	2641	2553	2668	0.384	0.334	0.321	75	63	63
13	9.0	0	2616	2394	2583	0.380	0.327	0.339	75	62	66
14	10.1	5.0	2174	1872	1967	0.325	0.302	0.302	50	42	50
15	10.6	5.0	2211	1680	1691	0.348	0.288	0.303	56	37	45
16	16.9	14.3	799	624	626	0.183	0.158	0.150	15	10	10
17	14.4	-2.4	1861	1769	1710	0.244	0.216	0.208	30	26	25
18	14.3	-2.4	1646	1543	1536	0.255	0.217	0.216	31	26	26
19	14.1	0	1669	1540	1623	0.250	0.216	0.221	31	25	26
20	14.9	5.1	1541	1389	1439	0.243	0.206	0.211	28	21	23
21	17.2	10.0	1227	858	956	0.199	0.150	0.172	18	11	15
22	13.5	10.0	1199	874	1012	0.170	0.179	0.199	20	15	18

* Integrated to 1.0-Ms

**Gages located below charge center

TABLE 4 MEASURED SHOCK WAVE VALUES

BURIED WELLHEAD

GAGE POSITION	RADIAL DIST. (FT)	VERTICAL DIST. (FT)	PM (PSI)			I (PSI-SEC)*			E (IN-LB/SQ-IN)*		
			COMP C-4	TNT	NM	COMP C-4	TNT	NM	COMP C-4	TNT	NM
1	9.6	8.7	1182	741	NR	0.287	0.161	NR	32	9.7	NR
2	10.4	9.6	1017	601	872	0.286	0.145	0.171	28	7.9	13.7
3	12.0	11.3	830	472	680	0.220	0.119	0.145	18	5.3	10.2
4	12.9	12.3	929	474	716	0.218	0.112	0.141	17.5	4.7	9.70
5	16.75	16.25	641	339	518	0.153	0.086	0.097	9.3	2.5	5.15
6	17.6	17.1	581	281	500	0.149	0.079	0.092	8.1	2.2	4.63
7	22.1	21.7	447	242	396	0.121	0.059	0.079	5.0	1.2	2.91
8	26.0	25.7	365	215	351	0.099	0.054	0.065	3.55	0.96	2.22
9	27.0	26.7	351	204	328	0.096	0.047	0.058	3.3	0.77	1.83
10	12.6	8.8	1386	481	994	0.218	0.102	0.103	19.6	3.5	9.86
11	13.3	9.8	1146	497	878	0.184	0.100	0.112	14.8	3.2	7.88
12	14.6	11.5	975	394	716	0.181	0.094	0.103	13.4	3.2	6.68
13	13.4	9.9	829	447	662	0.181	0.094	0.095	12.7	3.3	5.92
14	18.8	16.5	552	310	493	0.145	0.071	0.078	7.4	2.1	3.83
15	19.6	17.4	575	390	457	0.151	0.070	0.074	7.2	0.99	3.42
16	27.8	26.3	375	186	319	0.092	0.040	0.049	3.1	0.74	1.67
17	16.75	9.2	690	178	727	0.141	0.064	0.081	7.3	0.99	4.70
18	17.25	10.1	749	216	674	0.141	0.064	0.072	7.5	1.10	4.27
19	18.6	12.2	703	245	575	0.124	0.062	0.059	6.6	1.17	3.53
20	22.0	17.0	560	270	416	0.111	0.057	0.059	5.1	1.22	2.34
21			478	260	392	0.124	0.066	0.075	5.5	1.45	2.96
22	23.8	22.0	480	268	335	0.107	0.045	0.060	4.3	0.97	2.18

*Integrated to 1.0-Ms

TABLE 5 RELATIVE SHOCK WAVE VALUES

FREE WATER-CHNG'S IN CASINGS REL. TO CHG'S IN PVC CASES

GAGE POSITION	RADIAL STAND-OFF (FT)	VERTICAL STAND-OFF (FT)	PM (CASED/PVC)			I (CASED/PVC)			E(CASED/PVC)		
			COMP C-4	TNT	NM	COMP C-4	TNT	NM	COMP C-4	TNT	NM
1	5.0	-2.5	0.58	0.64	-	0.46	0.46	-	0.27	0.30	-
2	4.7	-2.5	0.51	0.54	0.40	0.58	0.38	0.34	0.22	0.22	0.19
3	4.0	0	-	0.58	0.61	-	0.42	0.42	-	0.26	0.26
4	4.0	0	0.58	0.52	0.64	0.49	0.45	0.46	0.30	0.25	0.31
5	6.4	5.0	0.55	0.36	0.45	0.56	0.40	0.33	0.29	0.16	0.16
6	6.7	5.0	-	0.35	0.55	-	0.32	0.40	-	0.14	0.21
7	10.8	10.0	0.37	0.32	0.42	0.47	0.35	0.39	0.40	0.13	0.17
8	14.1	13.5	0.45	0.39	0.39	-	0.38	0.40	-	0.16	0.17
9	15.1	14.6	0.46	0.36	0.39	0.38	0.24	0.38	0.22	0.16	0.16
10	9.6	-2.3	0.62	0.63	0.57	0.50	0.45	0.46	0.34	0.32	0.32
11	9.2	-2.3	0.66	0.61	0.66	0.49	0.40	0.44	0.35	0.27	0.31
12	9.0	0	0.66	0.66	0.69	0.51	0.45	0.43	0.36	0.31	0.31
13	9.0	0	0.61	0.57	0.60	0.49	0.43	0.38	0.34	0.29	0.23
14	10.1	5.0	0.57	0.54	0.54	0.46	0.44	0.44	0.28	0.25	0.29
15	10.6	5.0	0.66	0.50	0.55	0.48	0.43	0.47	0.33	0.23	0.30
16	16.9	14.3	0.43	0.36	0.40	0.44	0.39	0.37	0.25	0.18	0.19
17	14.4	-2.4	0.69	0.70	0.75	0.50	0.46	0.45	0.37	0.34	0.33
18	14.3	-2.4	0.71	0.67	0.67	0.52	0.44	0.44	0.37	0.32	0.32
19	14.1	0	0.68	0.64	0.67	0.50	0.43	0.45	0.36	0.30	0.32
20	14.9	5.1	0.63	0.61	0.65	0.51	0.44	0.45	0.35	0.28	0.31
21	17.2	10.0	0.68	0.49	0.57	0.47	0.37	0.42	0.31	0.20	0.27
22	13.5	10.0	0.51	0.39	0.51	0.32	0.34	0.38	0.21	0.17	0.20

TABLE 6 RELATIVE SHOCK WAVE VALUES - BURIED CHARGES REL. TO FREE WATER PVC

GAGE POSITION		RADIAL DIST.		$\frac{PM(BC)}{PM(FW\text{-}PVC)}$			$\frac{I(BC)}{I(FW\text{-}PVC)}$			$\frac{E(BC)}{E(FW\text{-}PVC)}$		
BURIED CHG.	FW PVC	BURIED CHG.	FW PVC	COMP C-4	TNT	NM	COMP C-4	TNT	NM	COMP C-4	TNT	NM
1	10-11	9.6	9.5	0.31	0.20	-	0.38	0.23	-	0.18	0.06	-
			9.17	0.31	0.20		0.41	0.23		0.18	0.06	
	12-13	9.6	9.0	0.30	0.19	-	0.38	0.22	-	0.15	0.05	-
			9.0	0.28	0.18		0.37	0.21		0.14	0.05	
2	7	10.4	10.5	0.34	0.24	0.40	0.50	0.20	0.26	0.33	0.05	0.10
			10.1	0.28	0.17	0.24	-	0.22	0.25	0.16	0.05	0.08
	14-15	10.4	10.5	0.31	-	0.28	0.42	-	0.27	0.16	-	0.09
3	22	12.0	13.4	0.36	0.21	0.34	0.41	0.23	0.27	0.19	0.06	0.11
				0.36	0.21	0.35	0.41	0.23	0.28	0.19	0.01	0.11
4	22	12.9	13.4	0.41	0.22	0.36	0.42	0.22	0.26	0.19	0.05	0.10
				0.40	0.21	0.37	0.41	0.21	0.28	0.19	0.05	0.11
10	22	12.6	13.4	0.60	0.22	0.50	0.41	0.20	0.20	0.20	0.04	0.11
11	22	13.3	13.4	0.50	0.22	0.45	0.35	0.19	0.18	0.15	0.04	0.09
13	22	13.4	13.4	0.36	0.20	0.34	0.34	0.10	0.18	0.13	0.04	0.07
12	9	14.6	15.0	0.55	0.25	0.48	0.40	0.14	0.23	0.18	0.04	0.10
	17-18	14.6	14.25	0.36	0.16	0.29	0.37	0.20	0.22	0.16	0.04	0.09
				0.42	0.17	0.31	0.37	0.19	0.21			
	8-19	14.6	14.08	0.53	0.22	0.43	86	0.19	0.20	32	0.04	0.08
				0.40	0.16	0.29	0.36	0.19	0.22	0.16	0.04	0.08
	20	14.6	14.92	0.41	0.17	0.32	0.38	0.20	0.22	0.17	0.04	0.09
5-17	16	16.75	16.75	0.35	0.19	0.33	0.37	0.21	0.24	0.15	0.05	0.10
				0.37	0.10	0.47	0.15	0.16	0.20	0.12	0.02	0.09
6	16	16.67	16.75	0.31	0.16	0.32	0.36	0.20	0.22	0.13	0.04	0.09
20	16	16.8	16.75	0.30	0.15	0.27	0.26	0.14	0.14	0.08	0.02	0.04
8	21	26.0	26.0	0.20	0.12	0.21	0.24	0.13	0.16	0.06	0.02	0.04
9	21	27.0	26.0	0.19	0.12	0.20	0.23	0.12	0.14	0.06	0.01	0.03
16	21	27.8	26.0	0.21	0.11	0.19	0.22	0.10	0.12	0.05	0.01	0.03
22	21	23.8	26.0	0.27	0.15	0.20	0.26	0.09	0.15	0.07	0.02	0.04

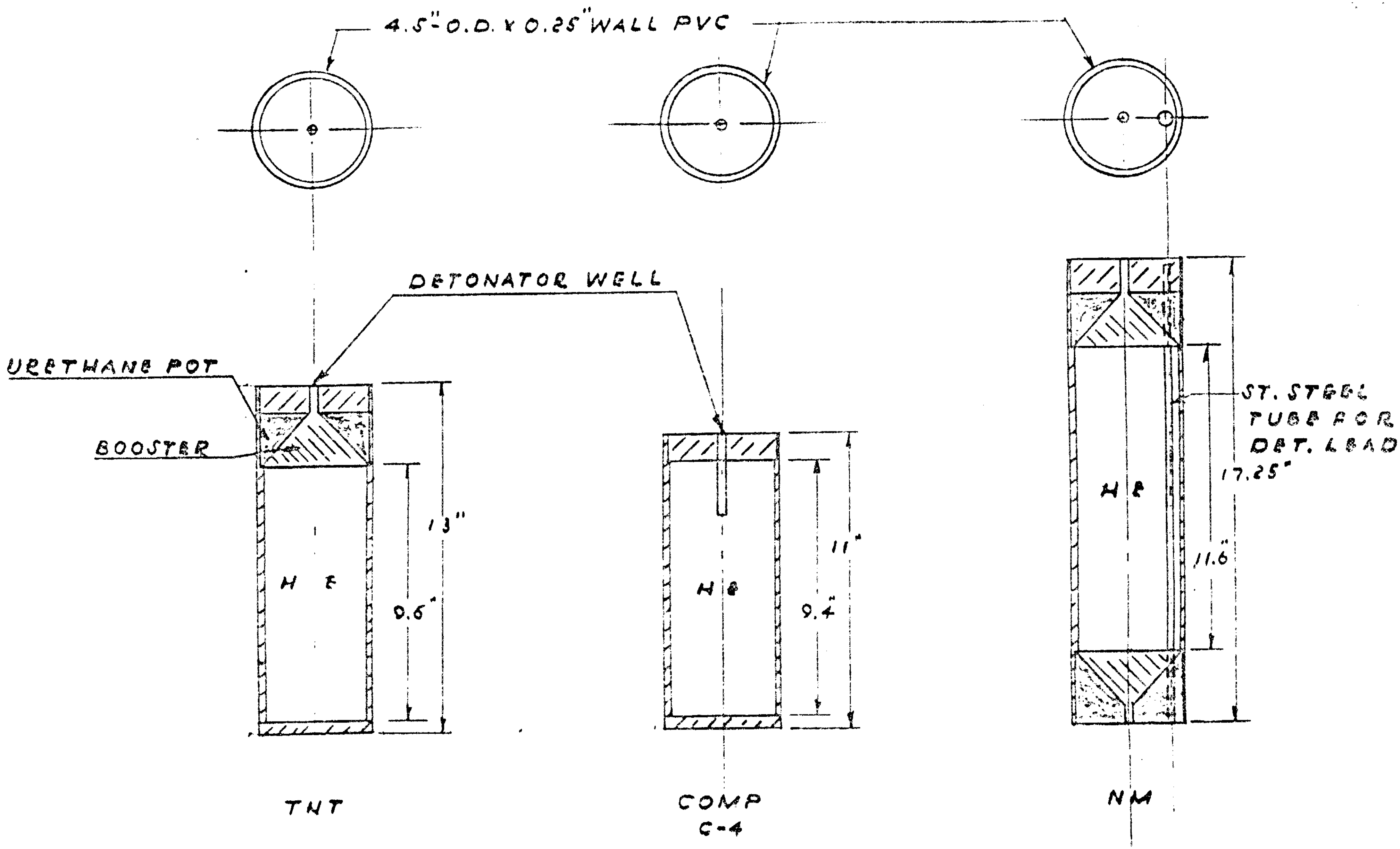


FIG. I CHARGE TYPES

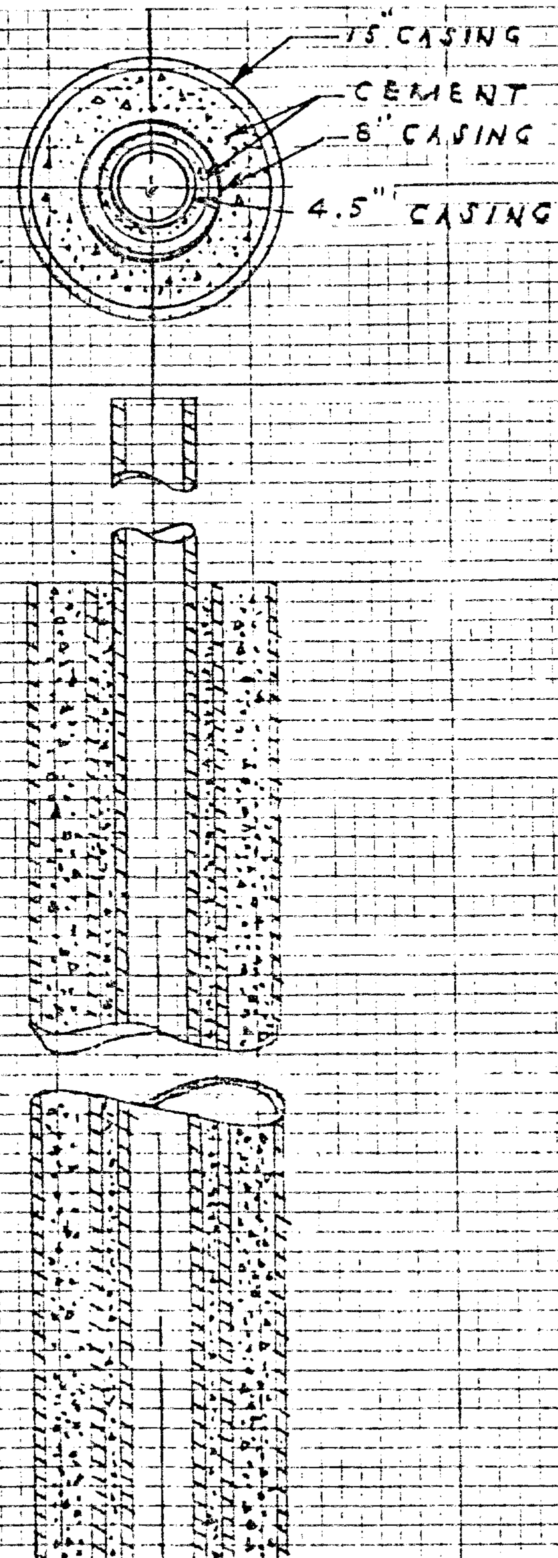


FIGURE 2 WELLHEAD COMPONENTS

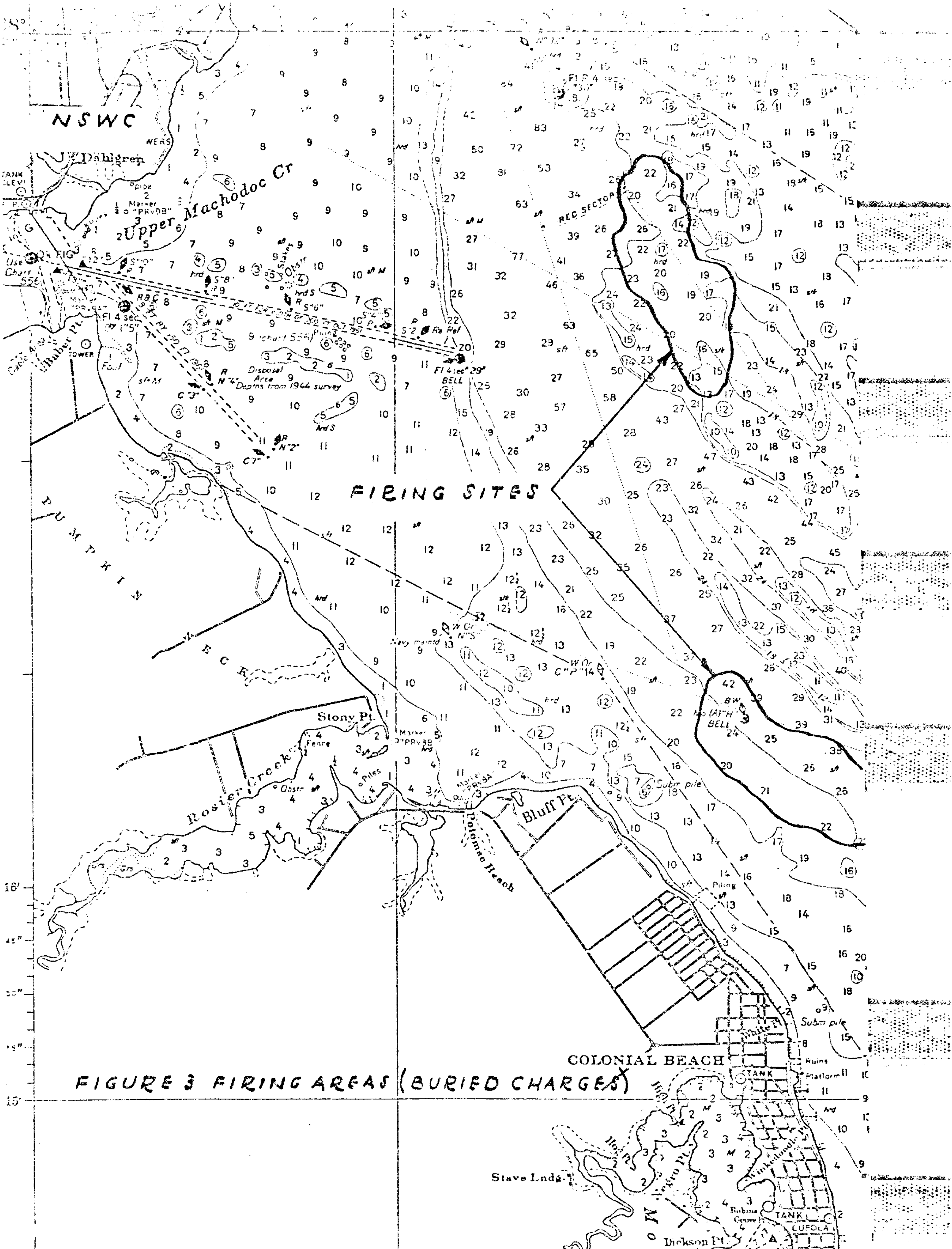


FIGURE 3 FIRING AREAS (BURIED CHARGES)

GAGE POSITION	RADIAL CHARGE TO GAGE DISTANCE (FT) STRING NO. 1	2	3
1-2	4.7		
3-4	4.0		
5-6	8.4		
7	10.8		
8-9	18.0		
10-11		9.3	
12-13		9.0	
14-15		10.3	
16		19.7	
17-18			14.2
19			14.0
20			14.3
21			17.2
22		13.5	

GAGE LEGEND

- ○ 1/4"-4 PILE
- ● 1/4"-1 PILE
- ◐ 3/8"-4 PILE
- ⊕ 1/2"-4 PILE

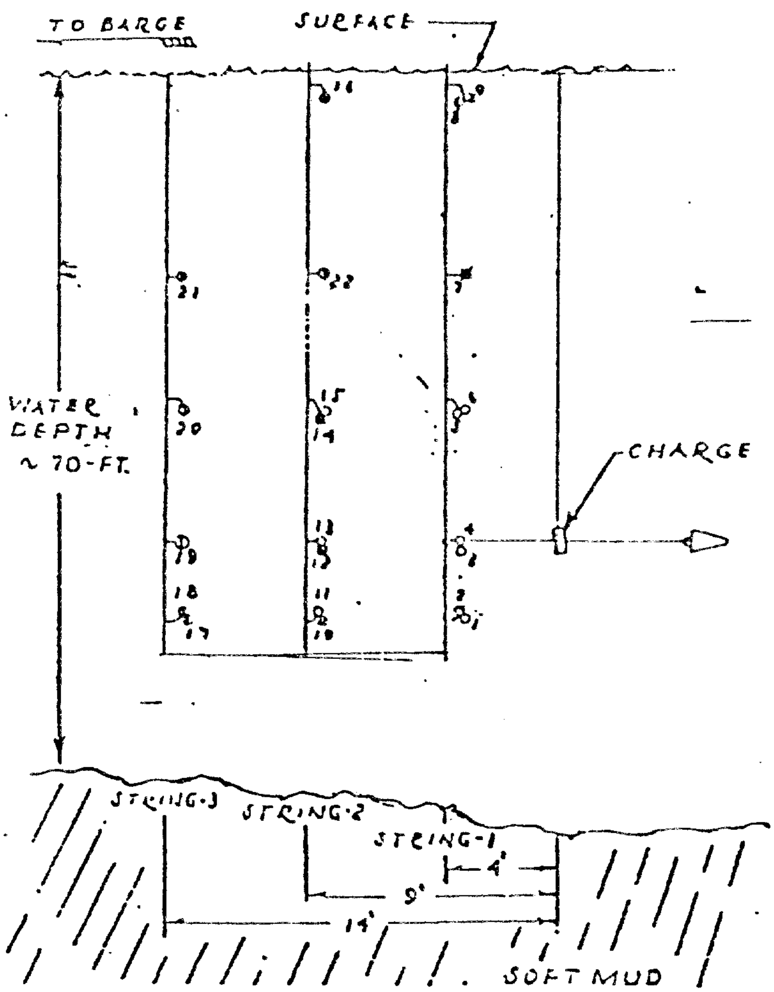


FIG 4 FREE WATER TESTS (CHARGES IN PVC CASE ONLY)

GAGE LEGEND

- ○ 1/4"-4 PILE
- ● 1/4"-1 PILE
- ⊗ 3/8"-4 PILE
- ⊕ 1/2"-4 PILE

GAGE POSITION	RADIAL CHARGE TO GAGE DISTANCE (FT) STRING NO. 1	2	3
1-2	4.7		
3-4	4.0		
5-6	6.4		
7	10.8		
8-9	18.0		
10-11		9.3	
12-13		9.0	
14-15		10.3	
16		19.7	
17-18			14.2
19			14.0
20			14.9
21			17.2
22		13.5	

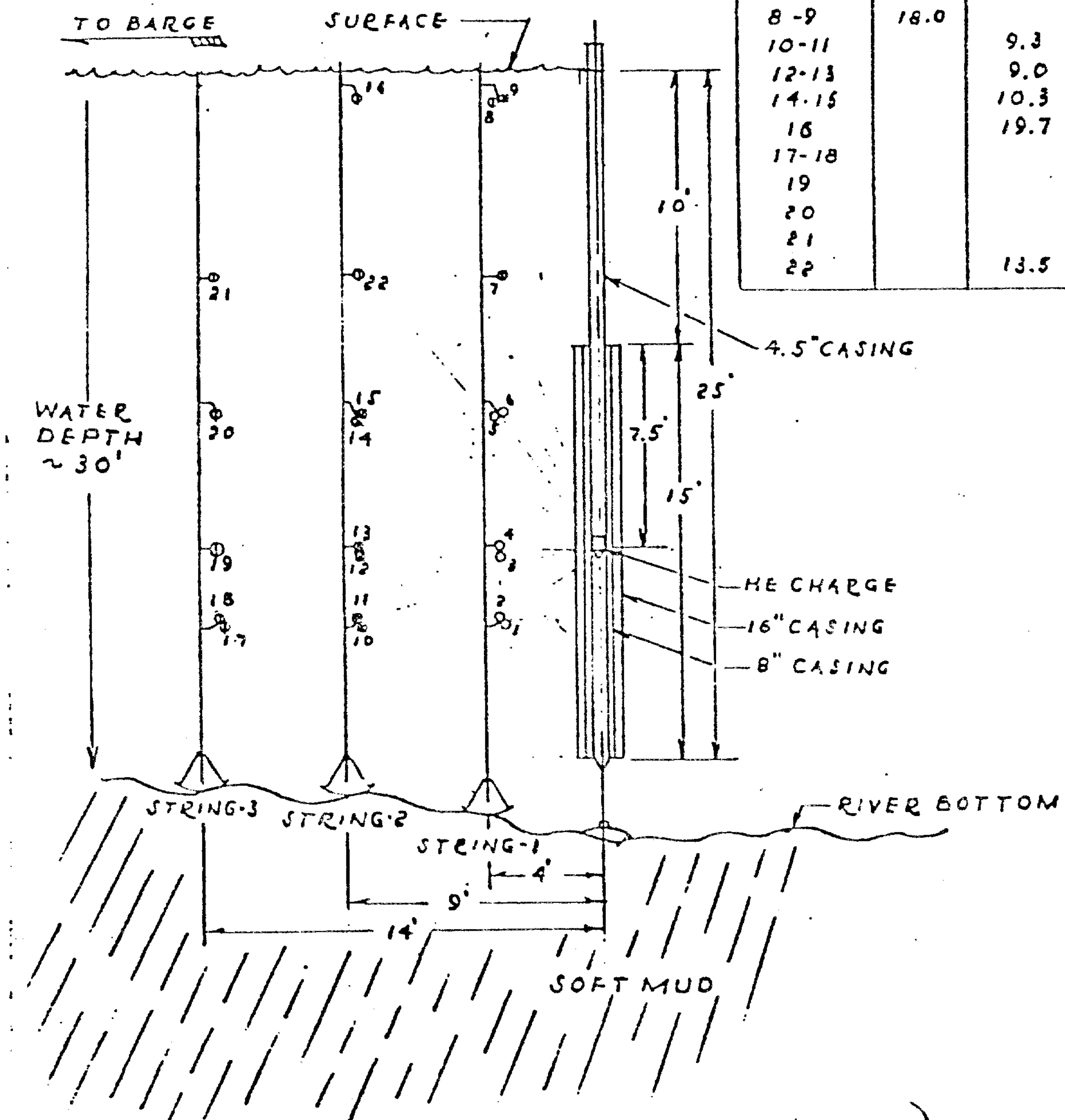
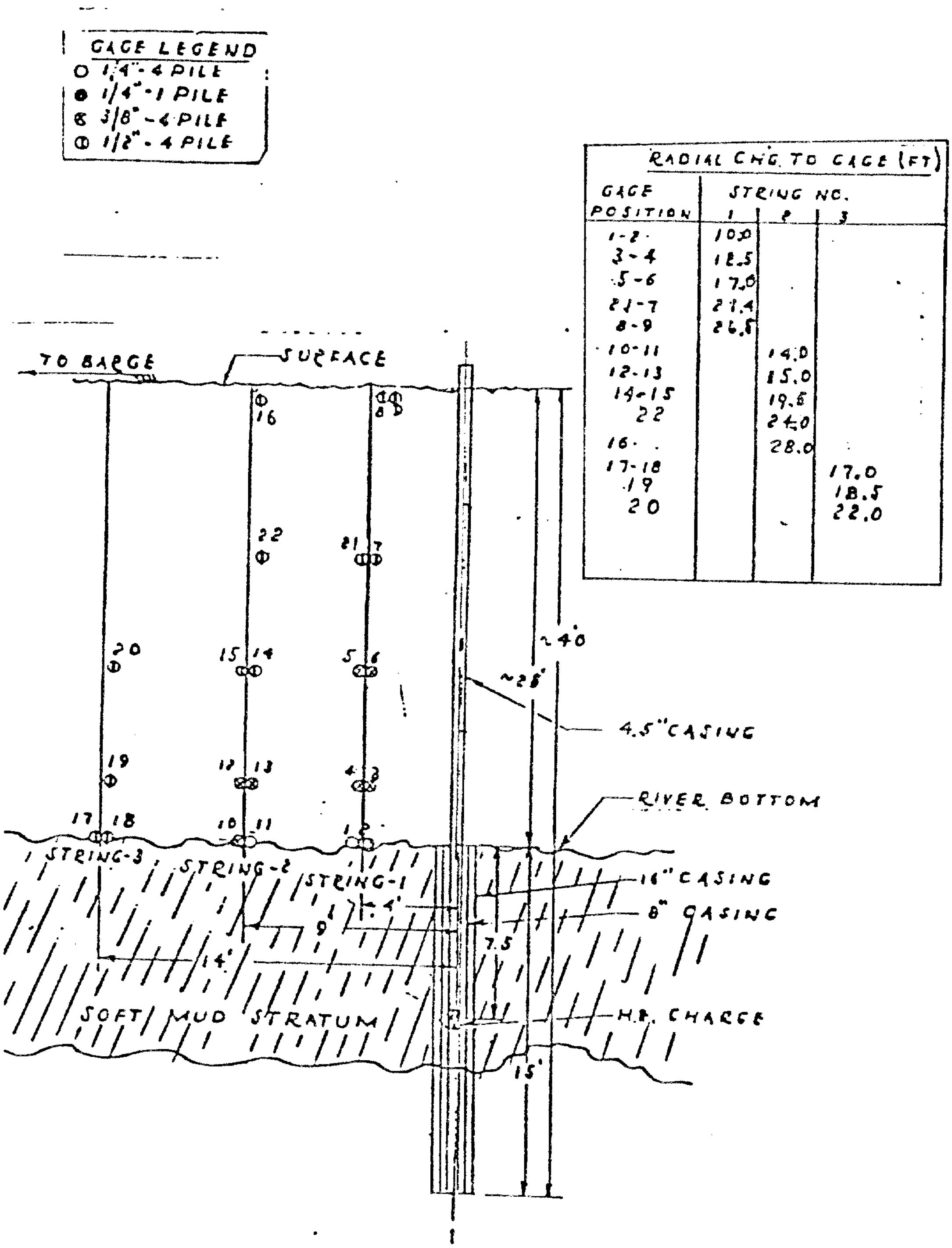


FIG 5 FREE WATER TESTS (CHARGES IN ~~STEEL CASINGS~~ WELLHEADS)



RADIAL CHG. TO GAGE (FT)

GAGE POSITION	STRING NO. 1	2	3
1-2	10.0		
3-4	12.5		
5-6	17.0		
21-7	21.4		
8-9	26.5		
10-11		14.0	
12-13		15.0	
14-15		19.5	
22		24.0	
16		28.0	
17-18			17.0
19			18.5
20			22.0

FIG 6 BURIED CHARGE TESTS

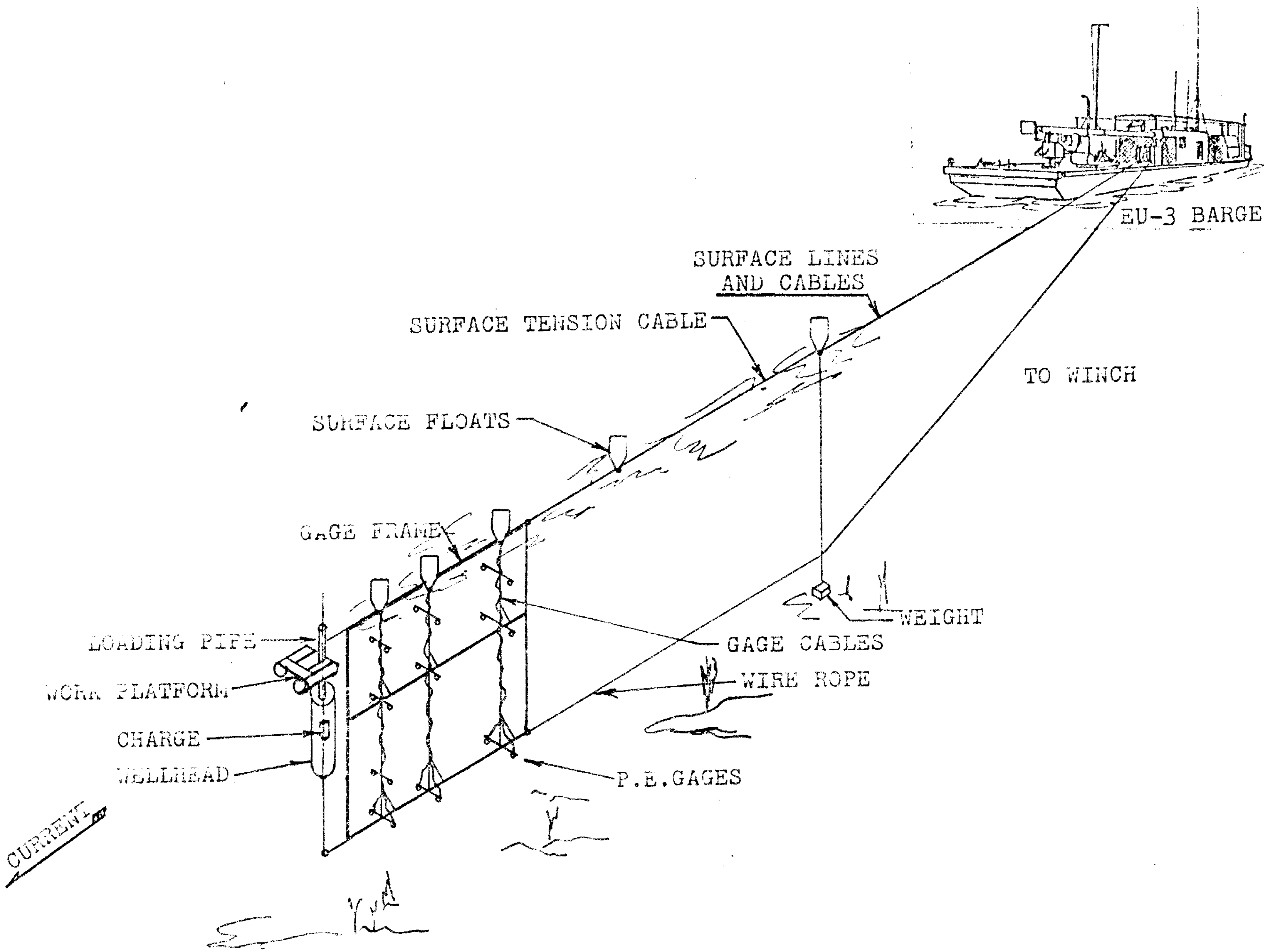


FIGURE 7 TEST ARRANGEMENT FOR FREE WATER WELLHEAD

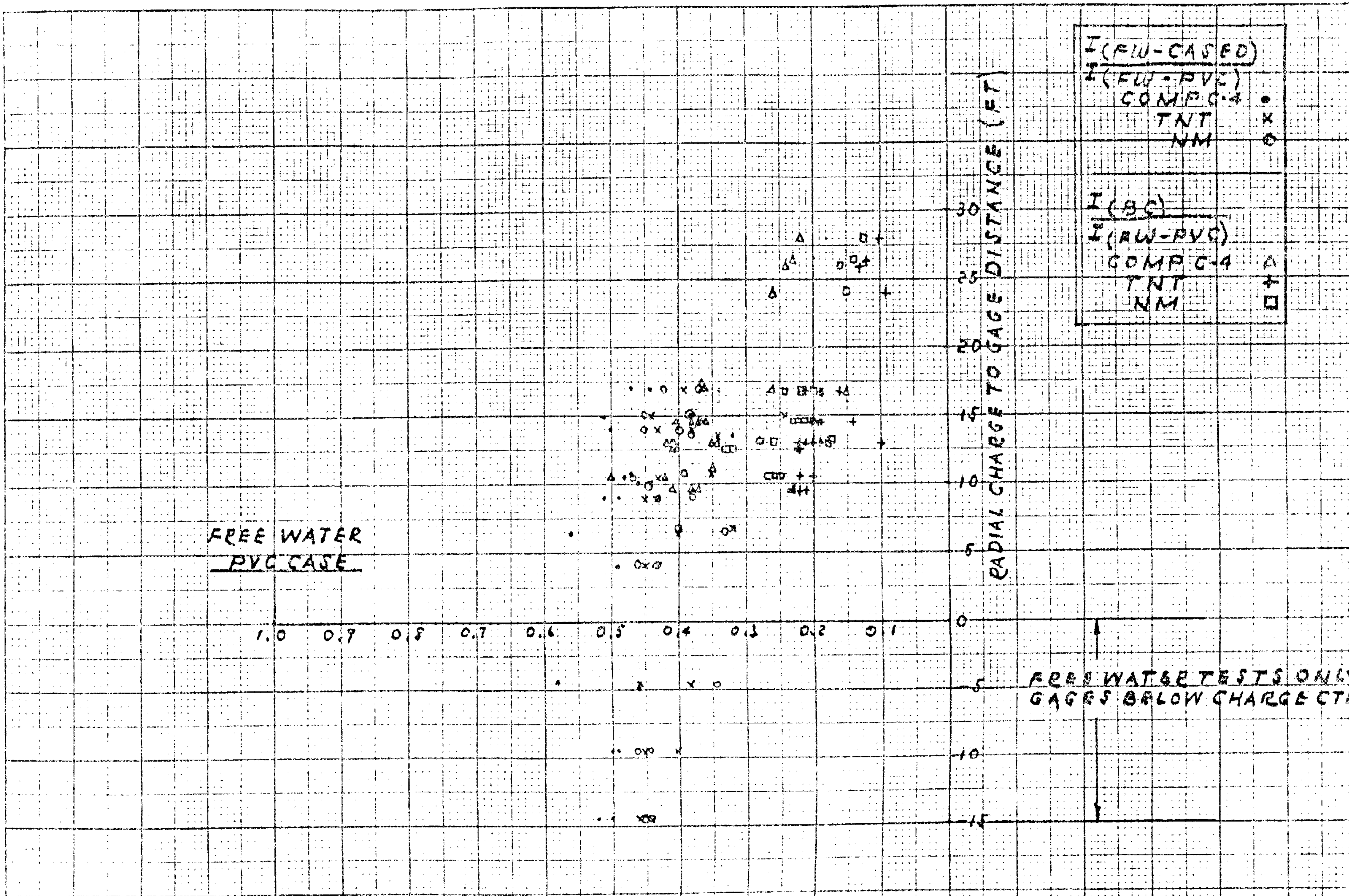


FIG RELATIVE IMPULSE

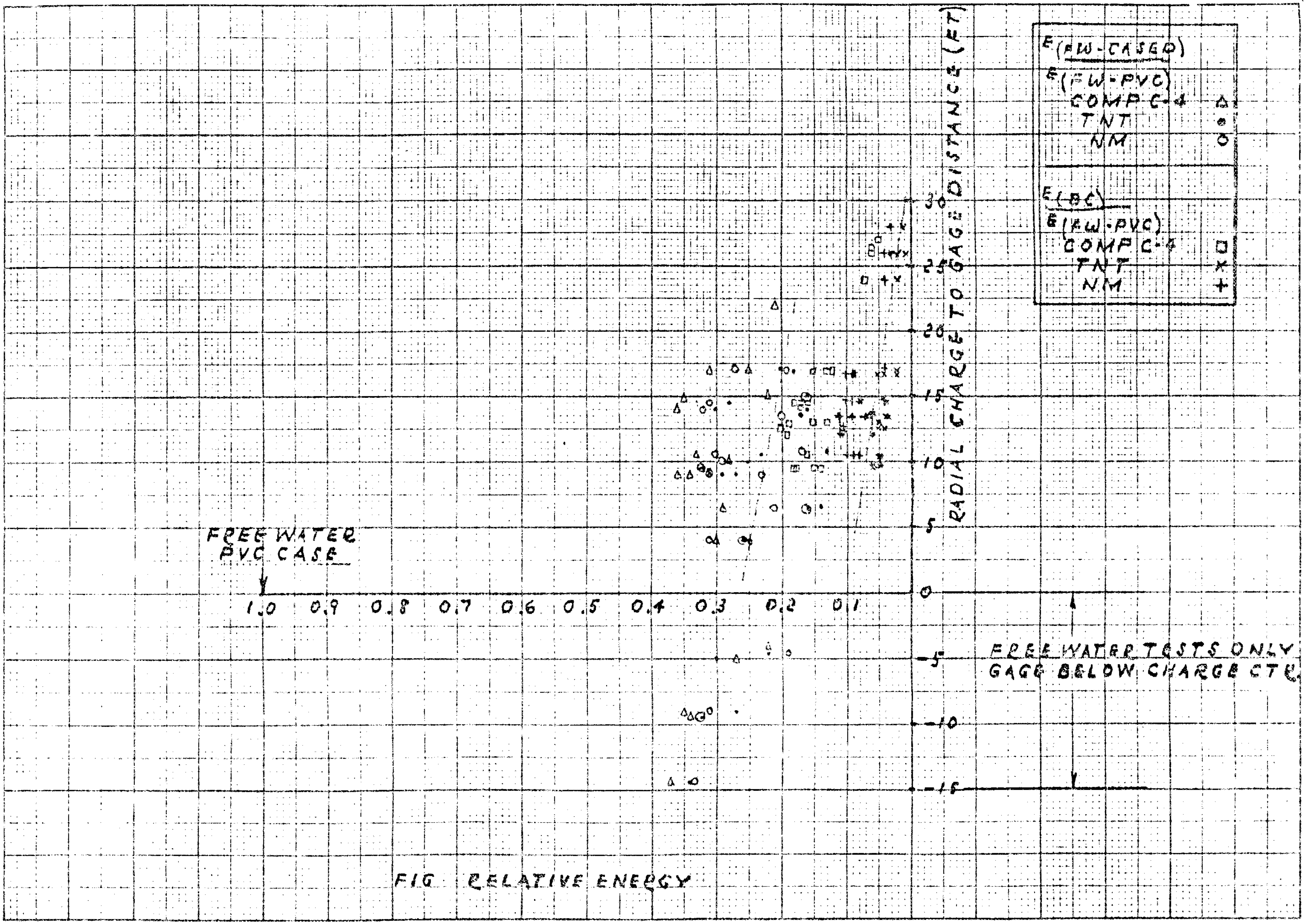


FIG RELATIVE ENERGY